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JOURNAL DE PHYSIQUE,
Colloque C6, supplément au n° 10, Tome 47, octobre 1986

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Résumé.- Des spectres de haute résolution du Nickel viennent d'être obtenus au J.E.T. dans le domaine de longueur d'onde 1.584 - 1.615 Å à partir d'un spectromètre à cristal courbe. On présente ici les premières données atomiques nécessaires à leur interprétation, elles correspondent aux raies de résonance du Ni XXVII et aux raies satellites des Ni XXVI et Ni XXV qu'elles soient diélectroniques ou d'excitation d'électrons de couches internes.

Abstract.- High resolution spectra of Nickel in the wavelength interval from 1.584 to 1.615 Å have been obtained recently at J.E.T. using a bent crystal spectrometer. Atomic parameters for resonance lines (Ni XXVII) and dielectronic and innershell satellite lines (Ni XXVI and Ni XXV) have been calculated for their interpretation.

I INTRODUCTION.

The study of the He-like resonance line satellites provides a convenient method for X-ray spectroscopic diagnostics of both astrophysical and laboratory plasmas at high temperature |1|. These satellite lines are due to innershell transitions of the type

$$1s^2\, n\ell \;-\; 1s\, 2\ell'\, n\ell'' \qquad \text{with } n \geq 2 \tag{1}$$

and they can be seen in high resolution spectra ($\lambda/\Delta\lambda \gg 1000$) of highly ionized atoms. They have been first observed from solar active regions and flares. For instance since several years many soft X-ray spectra of solar abundant elements have been obtained from spectrometers aboard spacecrafts as XRP on the Solar Maximum Mission |2|. On an other hand similar spectra have been observed from Tokamak plasma discharges |3, 4|. The radiation is emitted from high Z elements which enter the plasma as impurities from walls of the vacuum vessel (Fe, Cr, Ti, ...) and the plasma limiters (Ni) and is therefore of great interest for diagnostics. These diagnostic applications include measurements of the electron temperature, the ionic temperature, the ionization equilibrium and the impurity transport from intensity ratios.

This paper presents a part of the calculation for Ni carried out for all the He-like resonance line satellites corresponding to the transitions given by (1) for n = 2, 3, 4 i.e. the Li-like satellites. We also report some results for the Be-like satellites $1s^2\, 2\ell\, n\ell' - 1s\, 2p\, 2\ell''\, n\ell'''$ with n = 2, 3, 4. These data are being used for interpreting the satellite spectra of Ni XXVII which have been just obtained from the Joint European Torus (JET) the world's largest fusion experiment where Ni is the most important metal impurity.

II ATOMIC PROCESSES IN SUCH HOT PLASMAS.

The Tokamak plasmas are optically thin with an electron temperature in the range of 1.5 to 5 keV and an electron density between 10^{13} and 10^{14} cm^{-3}. The observed emissions are dominated by various processes such as (for the case of Ni ions):

- . collisional excitation from Ni XXVII;
- . innershell collisional excitation from Ni XXVI and Ni XXV;
- . collisional ionization from Ni XXVI;
- . radiative cascades from higher Ni XXVII excited levels;
- . dielectronic capture from Ni XXVII and Ni XXVI.

III DIAGNOSTICS FROM INTENSITY RATIOS.

Fig. 1 shows the energy level diagram of the principal lines used for diagnostic purposes

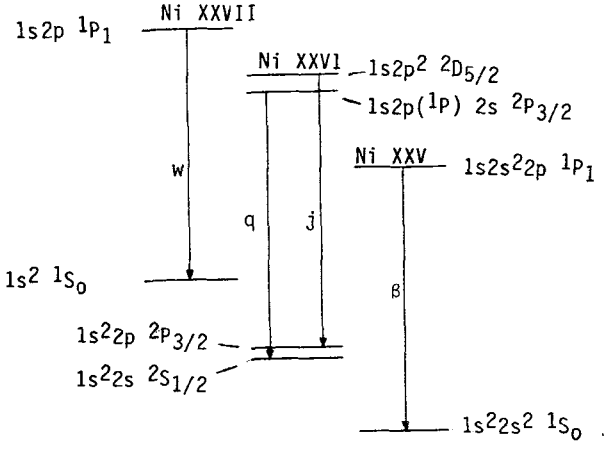

Fig. 1.- Energy level diagram of some Ni XXVII, Ni XXVI, Ni XXV excited states showing the w resonance line and associate satellite transitions.

a) Electron temperature.

The intensity ratio of a satellite line I_{sf} (from the level s to level f) populated by dielectronic recombination (for example j of Ni XXVI) to the Ni XXVII resonance line I_w can be written as

$$\frac{I_{sf}}{I_w} = F_1(Te)\ F_2(s) \qquad (2)$$

with

$$F_2(s) = g_s \frac{A_a^s\ A_r^{sf}}{A_a^s + \sum_{k<s} A_r^{sk}}$$

where A_a^s and A_r^{sf} are the autoionization and radiative transition probabilities in s^{-1}, from the level s, g_s the statistical weight of the level s,

and $F_1(Te) = \frac{2.07\ (-16)\ \exp(-\ E_s/k\ Te)}{C_w(Te)\ g_1\ \ Te^{3/2}}$

where E_s is the energy of the level s relative to the ground state of the He-like ion, g_1 the statistical weight of this ground state, $C_w(Te)$ is the effective collision rate for the line w and Te the temperature in K.

b) Relative abundances of ions for a given element.

When Te is known, the intensity ratio of a satellite line arising only by direct impact excitation of a 1s inner-shell electron (for example q of Ni XXVI and β of Ni XXV) to the resonance line w can be written as

$$\frac{I_q}{I_w} = \frac{N(\text{Ni XXVI})}{N(\text{Ni XXVII})}\ \frac{C_q(Te)}{C_w\ (Te)} \qquad (3)$$

where C_q is the inner-shell excitation rate.

IV ATOMIC PHYSICS CALCULATIONS.

To calculate the theoretical spectrum which allows these diagnostics, we have to compute a large number of atomic parameters as mentioned above. For this purpose the computation must be reliable and the computer code must provide this large amount of atomic data. That is the reason why we used the program package from University College of London |5, 6| completed by the program AUTOLSJ described in reference |4|. In the case of Ni a relativistic Hamiltonian has been used. All the wavelengths given in the tables were normalized to a resonance line wavelength (λ_w = 1.5885 Å) using a double difference correction $\Delta\lambda$ = + 0.0025 Å |7|.

a) He-like lines.

The intensities of the He-like lines as w are proportional to

$$Ne\ N(\text{Ni XXVII})\ C^{eff}$$

the effective collision rates C^{eff} are given in Table 1 for some temperatures of interest. They include the cascade contributions from the upper levels and the resonance effects due to the doubly excited levels of the Li-like ion |8|.

Te(10^6K)	1s2s $^3S_1$ (z)	1s2p $^3P_2$ (x)	1s2p $^3P_1$ (y)	1s2p $^1P_1$ (w)
20	3.30(-14)	1.57(-14)	1.54(-14)	5.27(-14)
30	1.14(-13)	5.26(-14)	5.58(-14)	2.19(-13)
40	2.13(-13)	9.00(-14)	1.03(-13)	4.45(-13)
50	3.05(-13)	1.19(-13)	1.45(-13)	6.79(-13)
λ(Å)	1.6036	1.5923	1.5965	1.5885

Table 1.- Effective collision rates, C in cm^3s^{-1}, from the ground state $1s^2\ ^1S_0$ of Ni XXVII including radiative cascades and collisional resonances.

LINE	Ident.	λ(Å)	$F_2(s)$
$1s2p^2\ ^2P_{3/2} - 1s^22p\ ^2P_{3/2}$	(a)	1.5975	1.42(14)
$1s2p^2\ ^4P_{5/2} - 1s^22p\ ^2P_{3/2}$	(e)	1.6071	1.35(14)
$1s2p^2\ ^2D_{5/2} - 1s^22p\ ^2P_{3/2}$	(j)	1.6008	5.50(14)
$1s2p^2\ ^2D_{3/2} - 1s^22p\ ^2P_{1/2}$	(k)	1.5981	3.71(14)
$1s2p^2\ ^2D_{3/2} - 1s^22p\ ^2P_{3/2}$	(l)	1.6032	4.62(13)
$1s2p^2\ ^2S_{1/2} - 1s^22p\ ^2P_{3/2}$	(m)	1.5935	5.53(13)
$1s2p3p\ ^2D_{5/2} - 1s^23p\ ^2P_{3/2}$	(d_{13})	1.5906	1.55(14)
$1s2p3p\ ^2D_{3/2} - 1s^23p\ ^2P_{1/2}$	(d_{15})	1.5899	1.30(14)
$1s2p3p\ ^2P_{3/2} - 1s^23p\ ^2P_{3/2}$	(d_5)	1.5897	6.40(13)
$1s2p3d\ ^2F_{7/2} - 1s^23d\ ^2D_{5/2}$	(h_{15})	1.5893	2.24(14)
$1s2p3d\ ^2F_{5/2} - 1s^23d\ ^2D_{3/2}$	(h_{13})	1.5881	6.41(13)

Table 2.- Calculated wavelengths and satellite line factors for Ni XXVI. (λ in Å and $F_2(s)$ in $10^{13}\ s^{-1}$).

$Te(10^6K)$	α
20	0.37
30	0.20
40	0.13
50	0.10

Table 3.- Contribution α of the unresolved satellite lines to the w resonance line of Ni XXVII with a spectral resolution of $\lambda/\Delta\lambda = 10^4$.

$Te(10^6K)$	$1s2p(^1P)2s^2P_{1/2}$ (r)	$1s2p(^1P)2s^2P_{3/2}$ (q)	$1s2p(^3P)2s^2P_{1/2}$ (t)	$1s2p(^3P)2s^2P_{3/2}$ (s)
20	1.22(-14)	3.65(-14)	1.01(-14)	6.76(-15)
30	4.85(-14)	1.49(-13)	4.04(-14)	2.26(-14)
40	9.53(-14)	3.00(-13)	7.97(-14)	3.84(-14)
50	1.42(-13)	4.55(-13)	1.19(-13)	5.01(-14)
λ(Å)	1.5998	1.5966	1.5936	1.5930

Table 4.- Electron excitation rates $C(cm^3\ s^{-1})$ from the ground state $1s^22s\ ^2S_{1/2}$ of Ni XXVI.

b) Li-like lines.

The two processes characteristic of the formation of these lines are the dielectronic recombination and the inner-shell collisional excitation. In the first case the intensity of the corresponding line is dependent of the factor $F_2(s)$ given in equation (2). Table 2 gives the most important dielectronic and well resolved lines for n = 2 and 3. With increasing n, the lines converge on their parent He-like line and it is necessary to estimate their contribution to the resonance line |7|. Table 3 shows this contribution $\alpha(Te)$ for a spectral resolution of $\lambda/\Delta\lambda = 10^4$.

In the second case, the intensity of the inner-shell excited lines is characterized by the collisional excitation rate C given in Table 4.

c) Be-like lines.

The processes for the formation of these lines are the same ones as the Li-like lines. Table 5 gives the parameters obtained for the most important dielectronic satellite lines.

LINE	λ	$F_2^*(s)$
$1s2s2p^2\ ^1D_2$ - $1s^22s2p\ ^1P_1$	1.6112	7.06
$^3D_3$ - $^3P_2$	1.6089	34.88
$^3P_2$ - $^3P_2$	1.6073	10.8
$^3D_2$ - $^3P_1$	1.6065	22.2
$^3D_1$ - $^3P_1$	1.6054	10.4
$^1D_2$ - $^3P_2$	1.6034	8.73
$1s2s^22p\ ^1P_1$ - $1s^22s^2\ ^1S_0$ (β)	1.6040	0.91
$1s2s2p3p\ ^3D_3$ - $1s^22s3p\ ^3P_2$	1.5994	6.08
$^1D_2$ - $^3P_1$	1.5985	6.22
$1s2s2p3d\ ^3F_4$ - $1s^22s3d\ ^3D_3$	1.5978	6.31
$1s2s2p3p\ ^3D_2$ - $1s^22s3p\ ^3P_2$	1.5969	2.64
$1s2s2p4p\ ^3D_3$ - $1s^22s4p\ ^3P_2$	1.5976	2.66
$^1D_2$ - $^3P_1$	1.5974	1.26
$1s2s2p4d\ ^3F_4$ - $1s^22s4d\ ^3D_3$	1.5971	3.12

Table 5.- Calculated wavelengths and satellite line factors for Ni XXV (λ in Å and $F_2^*(s)$ in $10^{13}\ s^{-1}$).

CONCLUSION.

The theoretical spectrum of Ni XXVII can be built using the atomic data given in the different tables. The adjustable physical parameters are the electron and ionic temperatures and relative abundance ratios of the different ion stages.

More complete calculations, including ionization, recombination, excitation of the Be-like levels and atomic parameters for the B-like lines will be given in a joint paper with JET collaborators.

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